

Introduction to Orbital Science

At each landing site on the surface of the Moon, the astronauts' activities are limited to distances of a few miles. In comparison with the total area of the surface of the Moon, the regions explored by the astronauts on foot or with the Rover are miniscule. They are frequently referred to as "point" samples. The desirability of extending our observations to larger areas is obvious. Indeed, several things can be done *in orbit* about the Moon that will allow us to extrapolate from the data obtained on the surface to the rest of the Moon. One of these things is photography; many photographs have been obtained from the command module on each of the previous Apollo missions. Both the number and quality of photographs obtained from lunar orbit on Apollo 15, and scheduled to be obtained on 16 and 17, have been greatly increased over those of earlier missions.

Several things other than photography can be done from lunar orbit. In these next few sections I will describe them.

The region of the Moon that was examined with orbital experiments on Apollo 15 is shown in figure 55. The coverage for the present mission, Apollo 16, is shown in figure 56. At the time of writing this guidebook (January 1972), the landing site for Apollo 17 had not been chosen. So I do not

show the orbital coverage for Apollo 17. Nonetheless, I expect that the total coverage for these three missions will exceed 20% of the Moon's surface for several of the orbital experiments and will exceed 5% for each of them.

Although some photographic tasks will be done in the command module, most of the experiments for the orbital science will be done with equipment located in the service module. The various orbital experiments include the following—a chemical group of three experiments (gamma-ray spectrometer, X-ray fluorescence, and alpha particle spectrometer), S-band transponder, mass spectrometer, several photographic cameras with a laser altimeter, and a subsatellite (with S-band transponder, particle shadows/boundary layer, and magnetometer).

The equipment for the orbital science experiments, carried in the service module, are all housed in a section that is termed scientific instrument module (acronym SIM). The location of the SIM in the service module is shown in figure 57. The location of the equipment for the individual experiments in the SIM is shown in figure 58. The names and addresses of the principal investigator of each orbital experiment are given in Table 5.

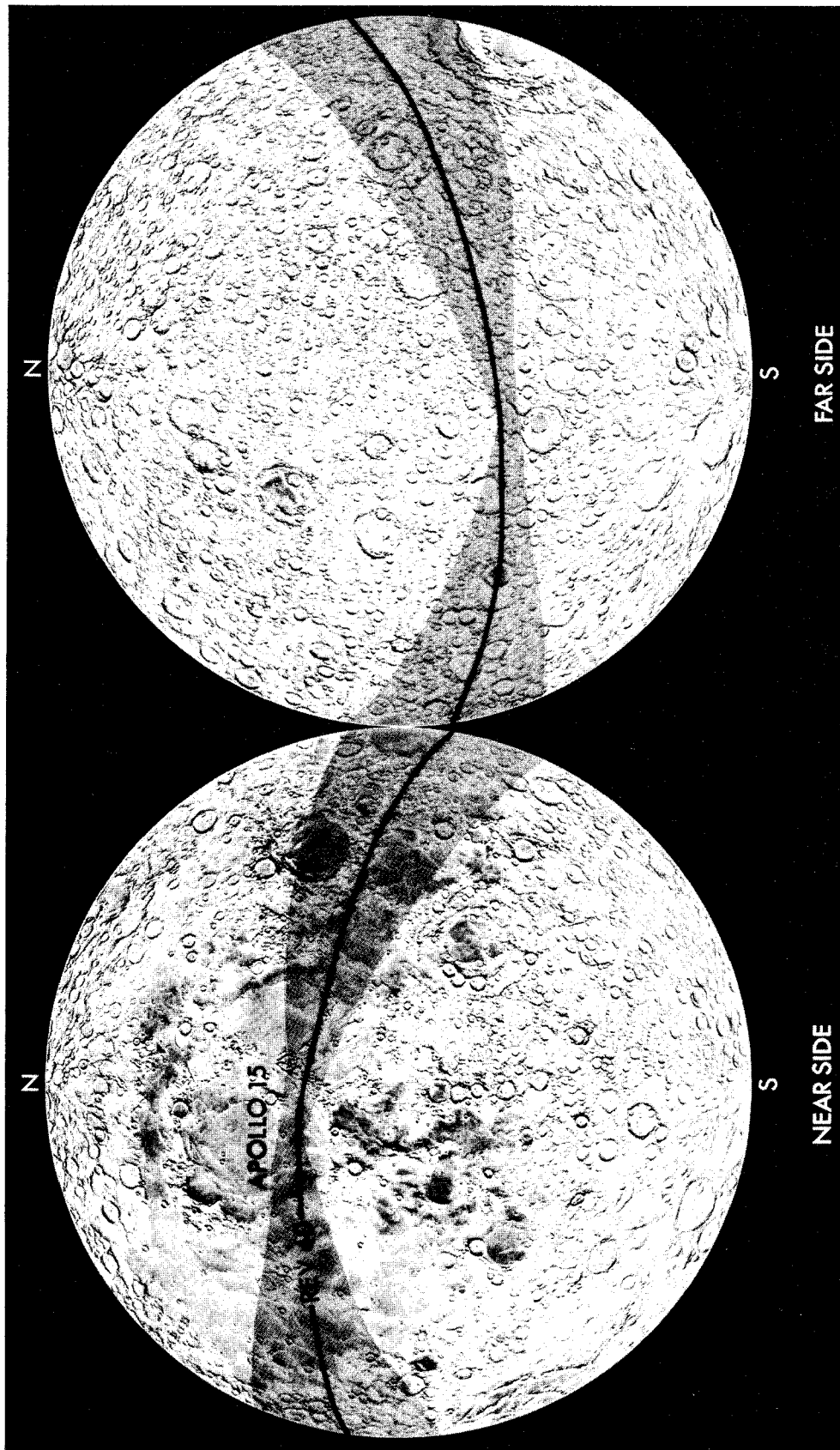


FIGURE 55.—Orbital Path for Apollo 15. Because the landing site of Apollo 15 was located well away from the equator the command module covered a rather large area of the Moon's surface. Data from the "chemical group" of experiments indicate the distribution of certain elements on the Moon's surface. The coverage of the farside of the Moon, never seen from Earth, is especially valuable. Almost 10,000 photographs were obtained during Apollo 15. If the 8×10 prints were laid side by side, they would extend almost 2 miles. BASE MAP COURTESY OF NATIONAL GEOGRAPHIC SOCIETY.

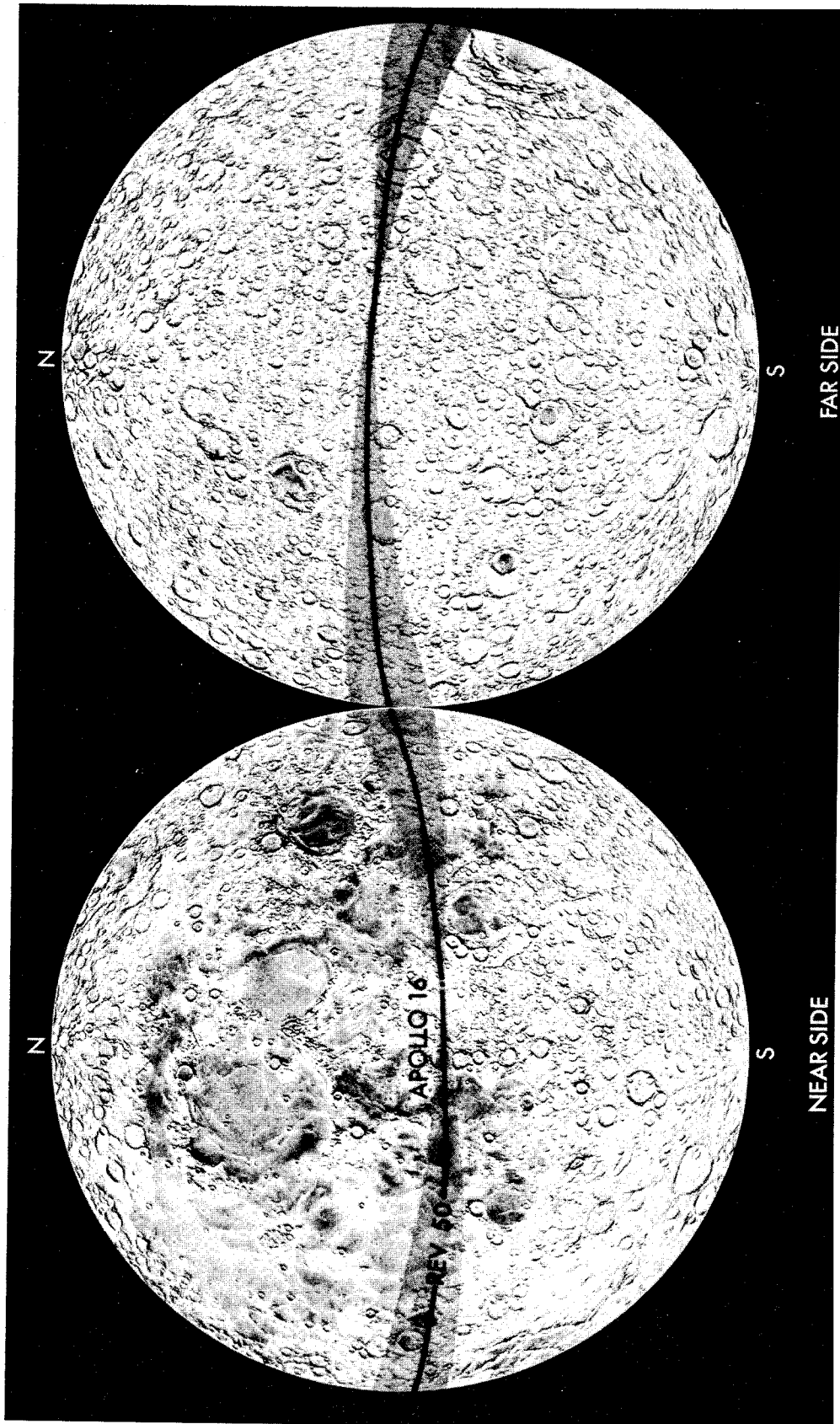


FIGURE 56.—Orbital Path for Apollo 16. See also caption for figure 55. BASE MAP COURTESY OF NATIONAL GEOGRAPHIC SOCIETY.

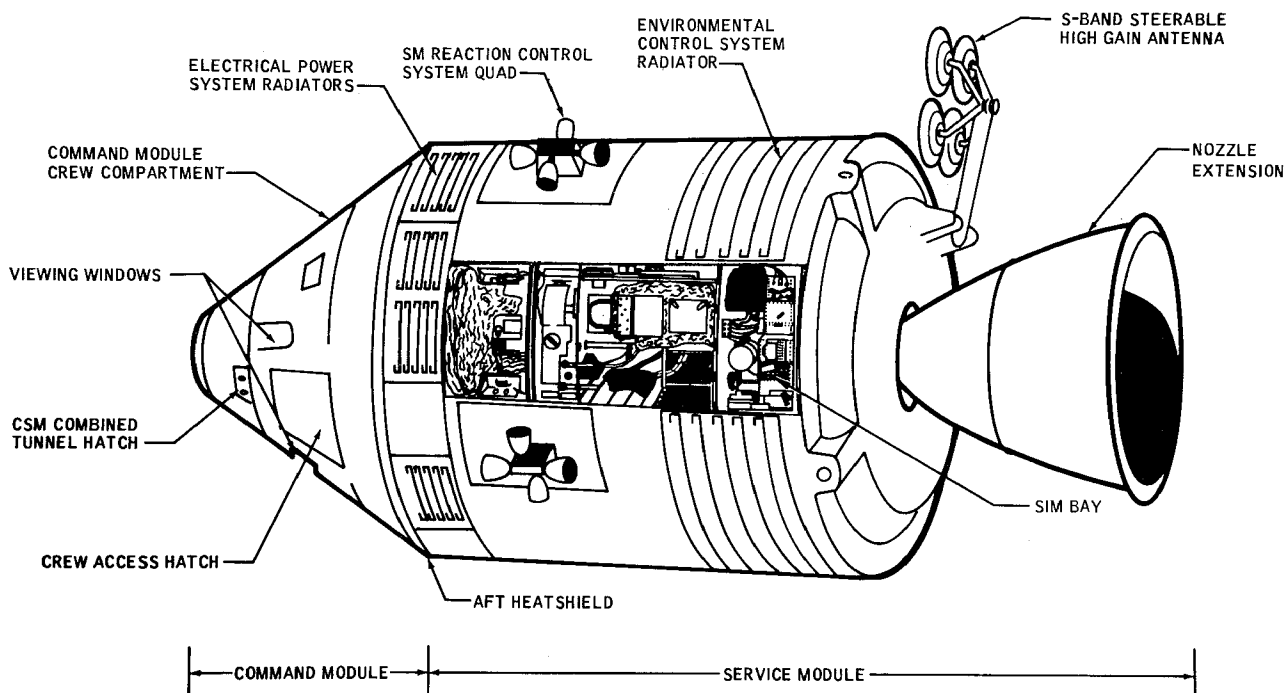
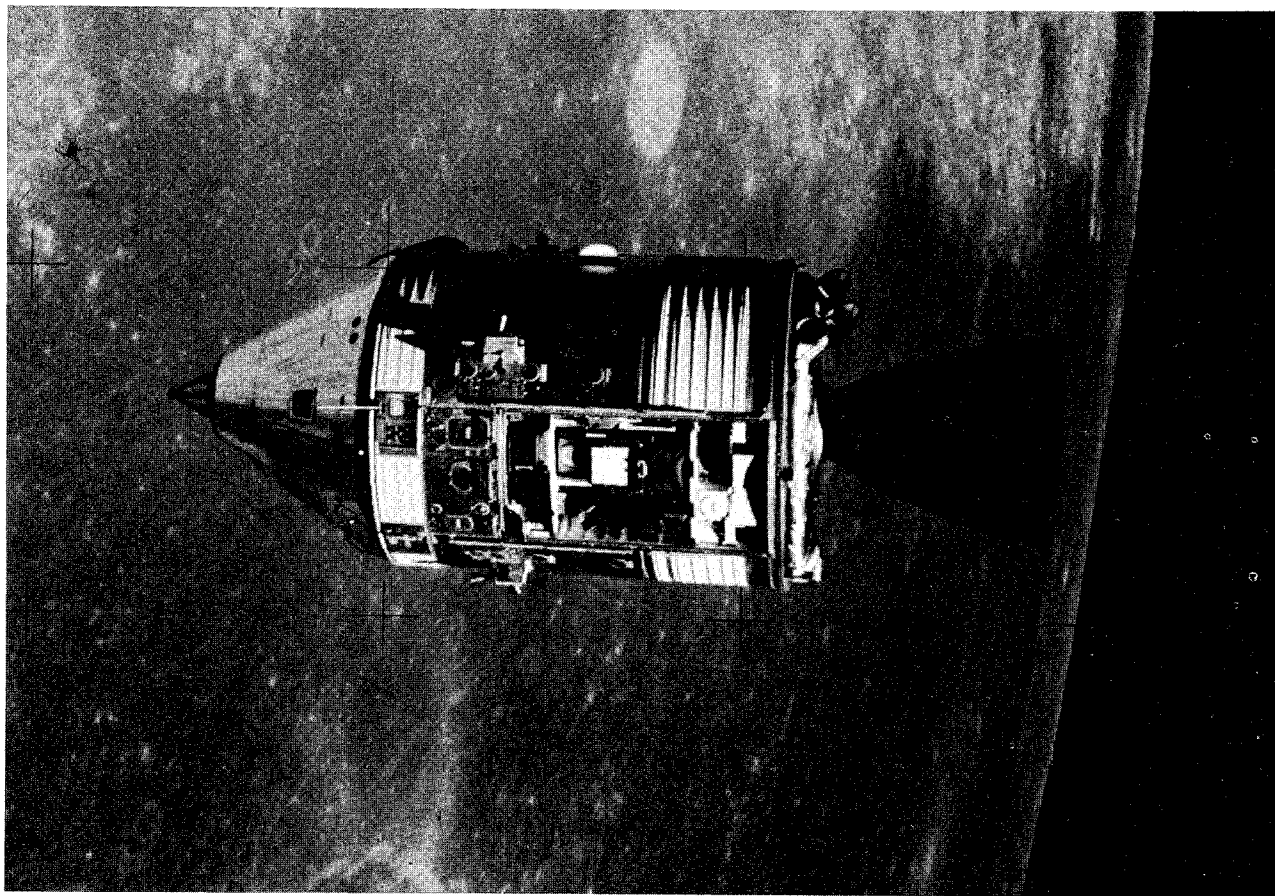


FIGURE 57.—Location of Scientific Instrument Module (SIM) in the Service Module, Apollo 15 photograph was taken from the LM with the Moon for background. NASA PHOTO AS15-88-11972. Sketch shows details and names.

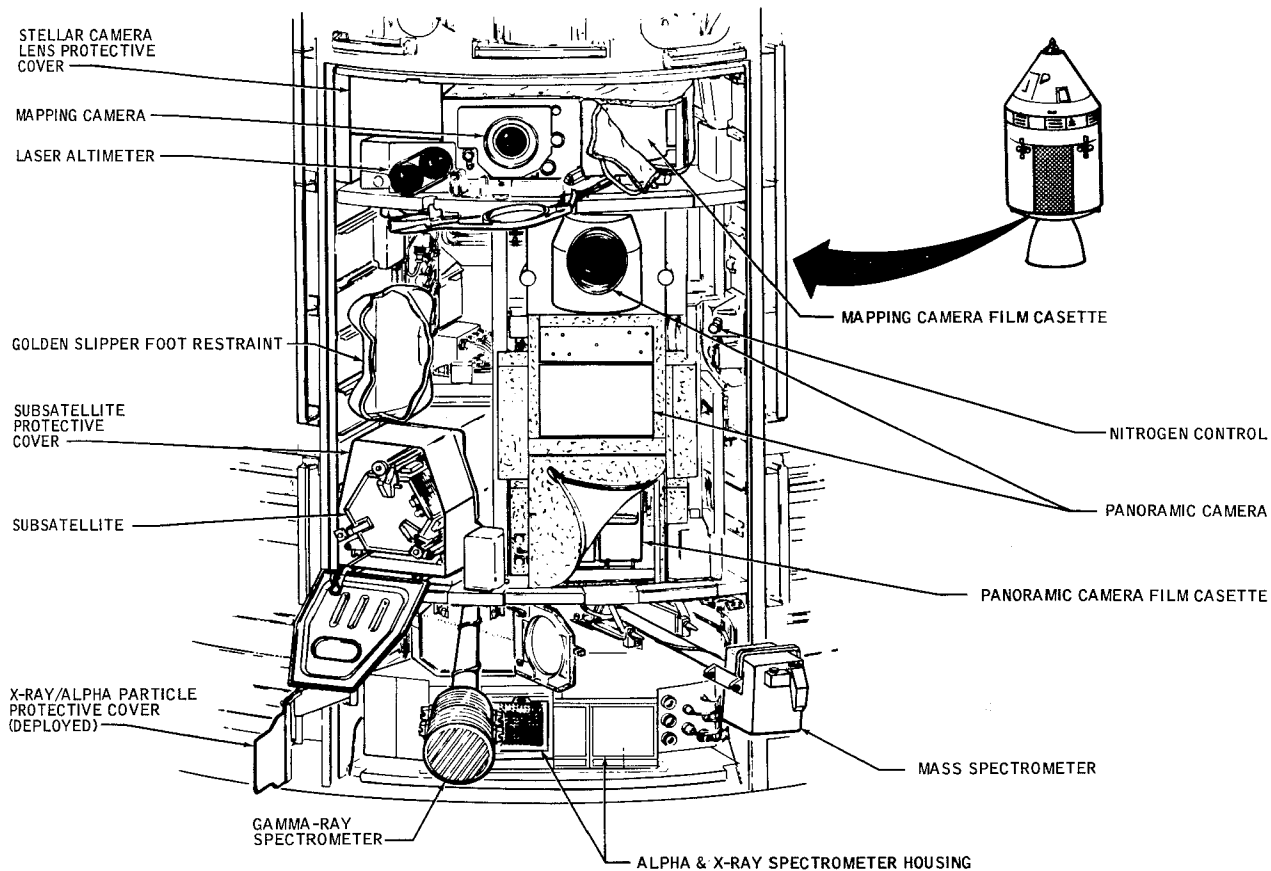


FIGURE 58.—SIM Bay. Shown here is the location within the scientific instrument module (SIM) of the equipment for each orbital experiment. The sensors for the gamma ray spectrometer and the mass spectrometer both extend outward on a boom about 25 feet when the instruments are in use. The subsatellite is launched while the service module is in orbit around the Moon; it remains behind in orbit after the astronauts leave lunar orbit to return home. Before the CM is separated from the SM the film cassettes must be retrieved. NASA PHOTO S-72-16852.

Orbital Science Activities

The door that covers the scientific instrument module (SIM) will be jettisoned about $4\frac{1}{2}$ hours before the spacecraft reaches lunar orbit. The door will continue past the Moon and be lost into space. By removing it *before* reaching lunar orbit, the astronauts keep the debris out of lunar orbit and remove the possibility of later contact with it and of later contact between the subsatellites and debris.

The initial lunar orbit is an ellipse with maximum distance from the Moon of 170 nautical miles and minimum distance 60 nautical miles. A nautical mile is 15% larger than a statute mile. A few hours later, a second rocket burn places the spacecraft into a 60×8 nautical mile orbit from which the LM will descend to the Moon after another $17\frac{1}{2}$ hours. During this $17\frac{1}{2}$ -hour period, the SIM experiments (X-ray, alpha particle, gamma ray, and mass spectrometer) and cameras will scan the lunar surface. The S-band transponder experiment also will be performed.

Then shortly before the LM touchdown, a third rocket burn of the orbiting CSM's rocket engine will circularize the orbit at 60 nautical miles. During the next 3 days while the LM remains on the surface of the Moon, all of the orbital experiments will be performed. The CSM will change the plane of its orbit about 20 hours before the LM liftoff so that it will be in the proper place to rendezvous with LM.

After rendezvous, various items, including the lunar samples and photographic film will be transferred from the ascent stage to the command module. Then the LM, of no further use to the astronauts, separated from the CSM, i.e. undocked, and will be crashed onto the Moon's surface to provide a source for the passive seismic experiment. About 20 hours after lunar liftoff, we change the position of the orbit around the Moon to increase the coverage of the Moon's surface with the orbital science experiments. Technically, this operation is called a plane change. In figure 2, you may have noticed that the orbit of the spacecraft lies in a plane. By

changing the orientation of the orbital plane in space, we can change the position of the ground track.

Several hours before leaving lunar orbit to return to Earth, the orbit will be changed again, this time to a 76×56 nautical mile orbit. This orbit was carefully designed to provide a one-year lifetime for the subsatellite with the orbit as close as possible to the Moon. The subsatellite with its 3 experiments (S-band transponder, particle shadows/boundary layer, and magnetometer) will be ejected from the SIM at about $5\frac{1}{2}$ hours before the astronauts leave lunar orbit bound for the Earth. The orbit of the subsatellite will change slowly with time and the spacecraft will eventually hit the Moon. We hope that the subsatellite will remain in orbit for at least one year. If we are lucky, it may remain considerably longer.

The total time in lunar orbit during which the SIM experiments and photography can be performed is about six days. None of the individual experiments will operate for the full time. The maximum time used by any experiment in lunar orbit is roughly 60 hours. Some experiments interfere with each other and so cannot operate simultaneously. For the cameras, the maximum operating time is set by the weight of the film which can be returned to Earth.

Let us look briefly now at each of the various orbital experiments.

LUNAR ORBITAL SCIENTIFIC EXPERIMENTS AND HARDWARE

In this section, I discuss each of the orbital experiments and the nature of the equipment. I hope to provide enough information so that you can understand the nature of each experiment. On the other hand, I do not intend to write a complete textbook on the physics of lunar experiments. It is my hope that I can provide enough elementary information on the experiments that you understand how the experiment works. I hope then to show you a brief glimpse of the results that were

obtained on the Apollo 15 mission. Undoubtedly there are many surprises yet to come from the Apollo 15 data; results from Apollo 16 will surely be equally exciting.

Photographic Tasks and Equipment (PTE)

The purposes of the orbital photography are to obtain high resolution panoramic photographs of the Moon's surface, to obtain high quality metric photographs, and to obtain elevation of the surface of the Moon along the ground track. Two cameras and a laser altimeter, all mounted in the SIM, are used. The location of each of the cameras is shown in figure 58.

The 24-inch panoramic camera, figure 59, is used to obtain high resolution panoramic photographs with both stereoscopic and regular (technically termed monoscopic) coverage of the Moon's surface. (Many photographs of the Moon have been obtained already. Representative sets of Apollo photos as full color lithographs suitable for framing can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D.C. See Bibliography, page 72, for descriptions of the sets available.) Several automatic features have been incorporated into this camera. For example, the camera rotates continuously in a direction across the path of the orbiting spacecraft in order to provide the panoramic scanning (hence the name of the camera). It also tilts forward and backward to provide stereo coverage. In addition, in order to prevent blurring of the image, the camera automatically compensates for the forward motion of the spacecraft. And finally, one sensor detects the ratio of the forward velocity to the height of the spacecraft above the Moon's surface and automatically corrects for it. All in all, I think that even the most avid camera enthusiast would agree that the 24-inch pan camera is a very fancy one. You might be interested in knowing that this camera will provide an image on the film from an orbital altitude of 60 miles that gives 3 to 6 feet resolution of the Moon's surface. That resolution means we can see on the photograph an object as small as 3 to 6 feet.

The astronauts must be careful to protect the camera's sensors from exposure to the Sun. Of course the "guards" against this happening are the people in Mission Control in Houston. Several of these sensors have no provisions to prevent damage if the Sun is viewed directly.

A low speed black and white aerial-type film is used. The cassette must be retrieved by one of the

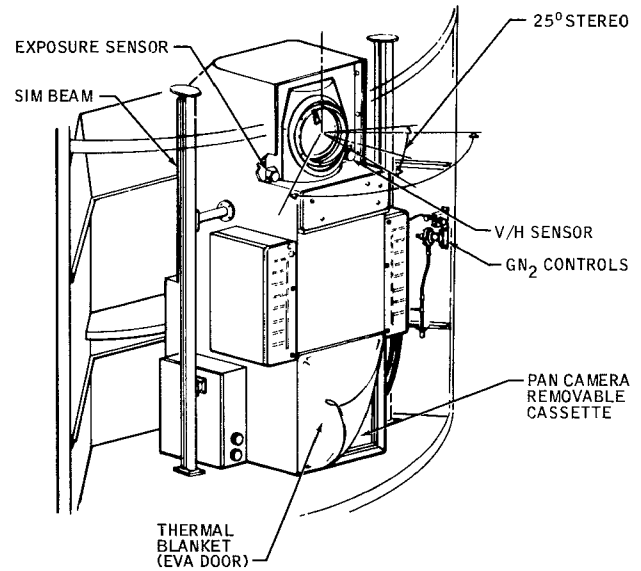


FIGURE 59.—24-inch Panoramic Camera. In operation, the entire assembly scans across the enclosure, a total of 108°. The camera lens tilts 25° forward and backward along the track of the spacecraft to provide stereo coverage. The film cassette is retrieved by the command module pilot on EVA in space.

astronauts, normally the CM pilot, during an EVA. The sequence of operations is indicated schematically in figure 60. The quality of the single photograph taken of Al Worden on Apollo 15 when he retrieved the film was not sufficient for me to reproduce the photo here. Instead, in figure 61, you can see a photograph from an earlier mission. Note the hose which is used to provide oxygen outside the CM. The back pack here is the Oxygen Purge System (OPS), similar to the PLSS in providing oxygen; it is used only in the (unlikely) event that the hose-supply fails.

Another camera in the SIM is the 3-inch mapping camera sketched in figure 62. It is really two cameras in a single assembly. Photographs of the lunar surface are obtained through the 3-inch cartographic lens and photographs of the star-field are taken through a different 3-inch lens pointed in exactly the opposite direction to permit the exact location of the camera to be determined later. Thus, our purpose in using this camera is to locate very precisely the surface features of the Moon. The resolution is considerably poorer than that of the pan camera being only 60 feet. But the metric camera provides photographs with extremely small distortions and on which points can be located with very high precision. (A basic rule of photography is that we cannot obtain in the

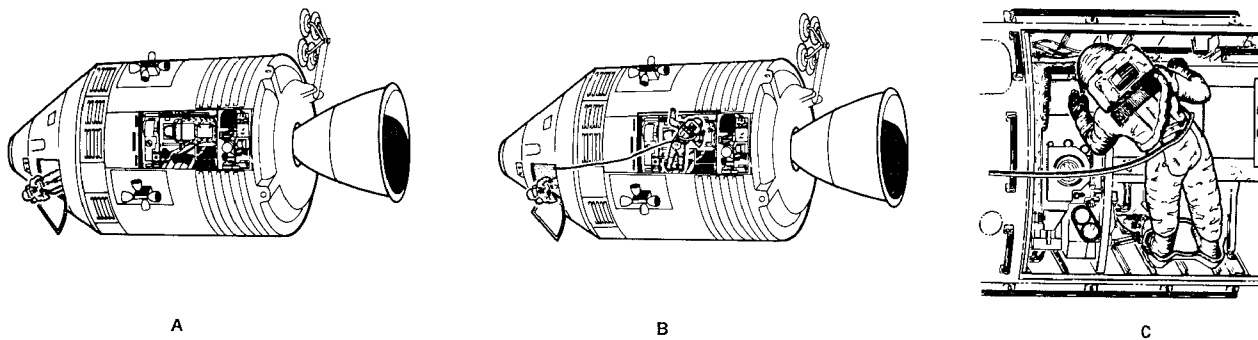


FIGURE 60.—Retrieving film from the SIM. In A, the astronaut is shown egressing through the CM hatch. All three astronauts must wear spacesuits to protect themselves against the vacuum of space. In B, an astronaut has moved to the vicinity of the SIM and is preparing to remove the film from one camera. He holds himself to the spacecraft by inserting his feet into special footholds, termed golden slippers because they were formerly gold colored. In C, he is removing the film cassette. The other astronaut documents the procedure with photographs and verbal descriptions. He also helps by passing the cassettes to the astronaut in the CM for storage. NASA PHOTO S-72-16323.

same camera *both* the lowest distortion possible and also the maximum resolution possible! Hence we have used two cameras: one designed for high resolution, the other for high precision and minimum distortion.)

The film used in the 3-inch camera is an intermediate speed black and white film commonly used in aerial photography.

The Laser Altimeter

The laser altimeter is used to obtain the elevation of the surface. It operates in much the same way that radar does. A pulse of light, produced by the laser, travels to the Moon's surface and is reflected back to a detector. The time of travel is measured. Since the speed of light is known (about 186,000 miles/second), we obtain the distance from the spacecraft to the Moon's surface. The orbit of the spacecraft is monitored continuously with tracking stations on Earth. The position of the spacecraft is known with rather high precision—say a few feet. The laser altimeter gives the distance between the spacecraft and the Moon's surface with a resolution of about 3 feet. Thus by subtraction, we get the elevation of the lunar surface.

The results of the Apollo 15 laser altimeter for one revolution are shown in figure 63. They are very exciting. Analysis of those results shows that the center of mass of the Moon is displaced about $1\frac{1}{2}$ miles from the center of volume in a direction that is approximately midway between Mare Serenitatis and Mare Crisium. We have known for about two years that these two maria are the sites

of the two largest gravity anomalies on the front side of the Moon. (See the section "S-band Transponder" for the discussion of gravity on the Moon.)

The two lowest elevations along the single revolution of Apollo 15, about $2\frac{1}{2}$ miles, are in Mare Crisium and Mare Smythii. There were earlier indications (from the land mark tracking data) that Mare Smythii was topographically low. The Apollo 15 laser data showed clearly that the ringed Maria Serenitatis, Crisium, and Smythii are truly basins and are 1.2 to $2\frac{1}{2}$ miles deep, Oceanus Procellarum is rather smooth and is depressed about $\frac{1}{2}$ mile. The Apennines are rather high standing, about $1\frac{1}{2}$ miles.

Chemical Group of Orbital Experiments

Three experiments, known as the Chemical Group, will be used on Apollo 16 to obtain data that will help us to extrapolate what we learn from the study of the Moon at the Apollo 16 site. In each of these experiments, we measure something that is related to the composition of the Moon's surface over an area immediately below the orbiting spacecraft. Each of the sensors "sees" a finite area on the Moon's surface. Accordingly, a measurement at any point along the orbital path is an *average* value for several square miles of Moon immediately below the spacecraft. Let's examine each of the three experiments in the Chemical Group.

X-ray Fluorescence Experiment (XFE).—In this experiment we use two phenomena that you are almost surely familiar with, although you may

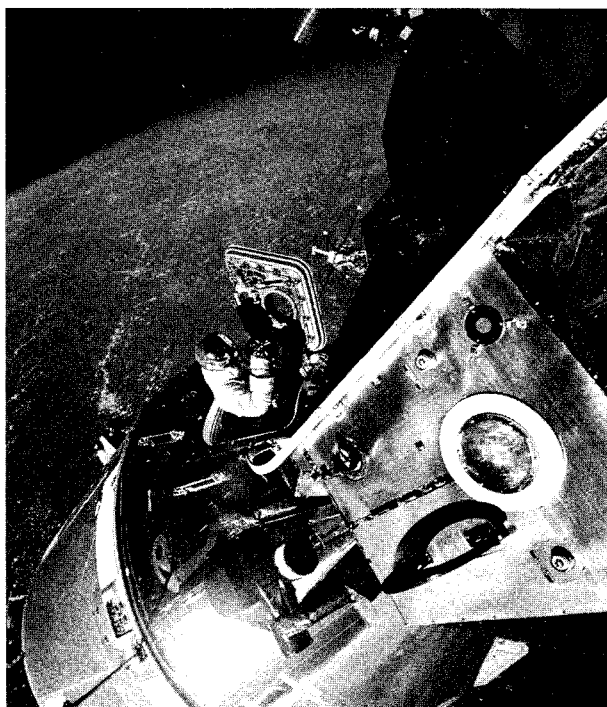
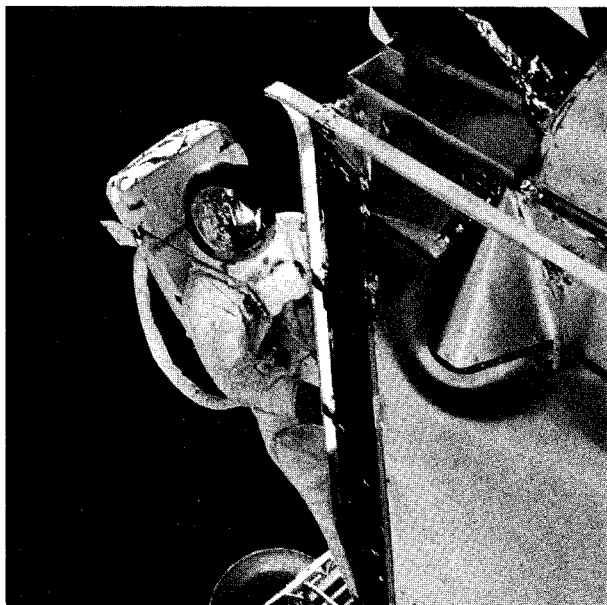


FIGURE 61.—EVA in Space. Work in space when an astronaut is outside the protective shell of the spacecraft is always exciting. It is also dangerous and the astronaut must be extra careful. On Apollo 16, the film from the cameras in the SIM must be recovered in this way. Shown here is Astronaut Schweickert during an EVA on Apollo 9. The umbilical hose that connects him to the spacecraft furnishes oxygen and also prevents him from drifting away. Astronaut Dave Scott in the hatch is describing the activities of Schweickert and taking documentary photographs. NASA PHOTOS AS9-19-2995 and AS9-02-3064.

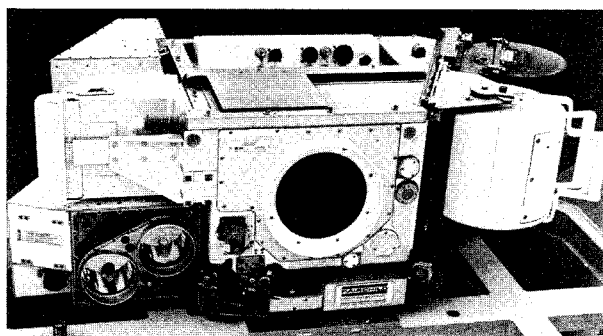
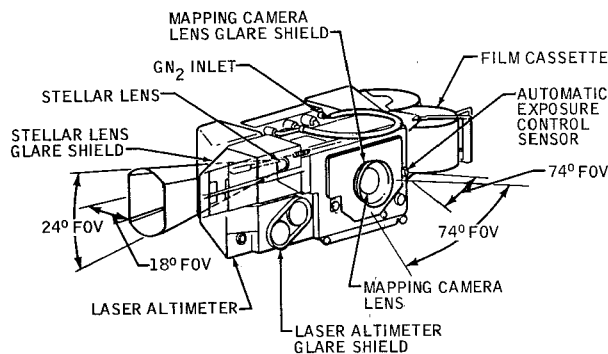


FIGURE 62.—Three-inch Mapping Camera and Laser Altimeter. This camera contains two complete cameras, one for photographing the Moon's surface, another for photographing the stars to obtain precise location of the camera in space at the time each photo is taken. The laser altimeter provides data on the altitude of the spacecraft with a precision of 1 meter (about 1 yard). The film cassette is retrieved by the CM pilot before the CM is separated from the SM. The location of this camera in the SIM bay is shown in Figure 58. Above, we see a simple line drawing. Below, we see a photograph of the camera. Gaseous nitrogen is used to maintain pressure in the camera.

never have thought of them working in combination. X-rays, discovered about 75 years ago by W. K. Roentgen, are used nowadays for many things—to “see” broken bones, decayed teeth, the flow of blood in arteries (when mixed with a suitable dye), and so on. I know of no better illustration of the great *practical* benefits that come from the laboratories of *pure* research. Within 3 months of Roentgen's discovery, X-rays were being used in a nearby hospital as an aid to surgery. There are many other nonmedical uses also. For example they are also used to identify many substances, including minerals.

X-rays have many of the properties of light; they travel in straight lines, they are electromagnetic waves, they can be diffracted, they can be reflected, and so on. Like light, they also darken photographic film. They *can* be detected and

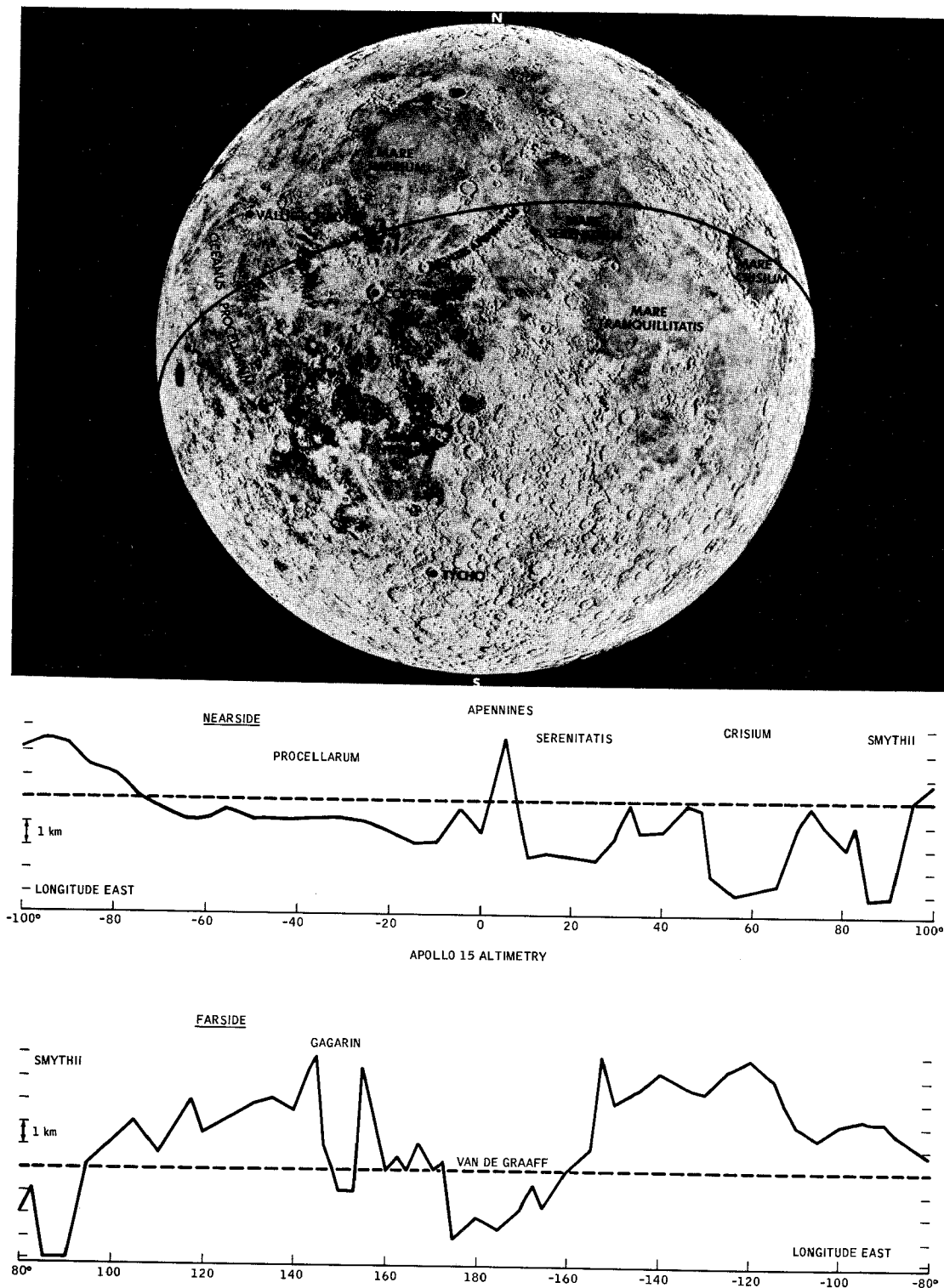


FIGURE 63.—Results of the Apollo 15 Laser Altimeter. Data are shown for one revolution only. The elevation of the surface of the Moon along that single ground track (above) is shown in diagram. The dashed line represents the elevation of a sphere with radius of 1737 km. Based on work of William Kaula in the Apollo 15 Preliminary Science Report. NASA PHOTOS S-72-16337 and S-72-16322.

measured by the well known Geiger Counter used in prospecting for radioactive minerals but usually more sophisticated instruments are used today.

Fluorescence is the phenomenon on which the very familiar fluorescent light bulb is based. It involves the displacement of an electron from its most comfortable orbital position in an atom. When the electron returns to that position, it releases energy in the form of light. The fluorescent material in the light bulb is the thin white coating on the inner surface. Of course the light bulb has been carefully designed so that most of the radiation is in the form of visible light. For most solids though the energy released by the returning electron is in the form of X-rays.

One of the standard techniques for the identification of an unknown substance is that of X-ray fluorescence. In this technique, the substance is bombarded with X-rays. The incident X-rays knock electrons out of their most comfortable orbital positions. When these electrons return, other X-rays are produced with wavelengths and energies that are characteristic of the material. Because no pair of elements produce patterns of fluorescent X-rays that are exactly alike, we can identify the elements present in the material by studying its fluorescent X-ray pattern. So, in principle at least, all we need to do in order to measure the chemical composition of the Moon is to bombard it with X-rays and measure the resultant X-ray pattern. The practical situation is slightly different, but not greatly!

For the source of X-rays with which to bombard the Moon, we use the Sun. We have known for a long time that the Sun is an excellent source of X-rays. In figure 64, we show schematically the Moon being bombarded with solar X-rays and the production of fluorescent X-rays by the lunar material. These fluorescent X-rays are then detected and measured with the XFE equipment.

Under favorable conditions, the experiment can detect and measure the amounts of lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, neon, sodium, magnesium, aluminum, and silicon. The most common of these elements in lunar rocks, as well as terrestrial, are magnesium, aluminum, and silicon.

The equipment on board the SM that we use to measure the X-rays is simple in principle but includes very sophisticated electronic devices. It is shown schematically in figure 65. It consists of a collimator, proportional counter, and considera-

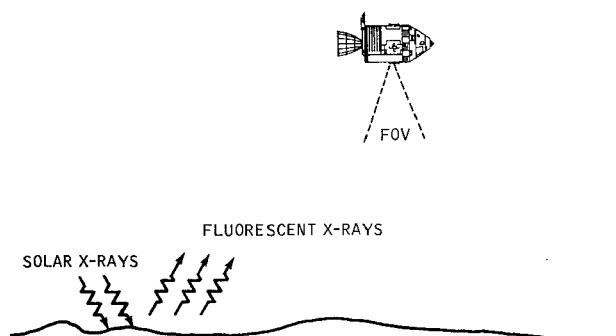


FIGURE 64.—X-ray Fluorescence Experiment. X-rays from the Sun hit the Moon's surface. They excite the atoms of the lunar material and produce fluorescent X-rays. The fluorescent X-rays are characteristic of the material and are detected and measured with equipment on board the service module. The absence of a lunar atmosphere is necessary for this experiment to operate successfully. Shown also is the field of view (FOV) of the instrument.

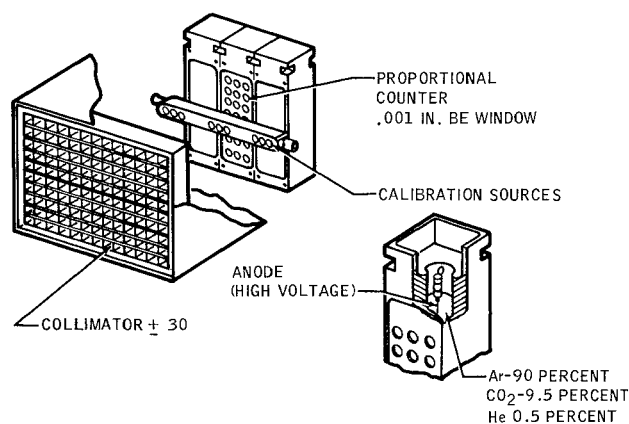


FIGURE 65.—X-ray Fluorescence Equipment. The collimator is a grid of tubes that restricts the viewing angle of the proportional counter; it is necessary in order to view small area (say a few square miles) of the Moon's surface at any particular time. The proportional counter provides an electrical voltage proportional to the energy of incident X-rays. It uses a mixture of the gases argon, carbon dioxide, and helium. The electronics package which is used to process the signals for radio transmission to the Earth is not shown in this figure.

ble electronics gear. The collimator is used to restrict the surface area of the Moon viewed by the equipment. The heart of the equipment is the proportional counter. It produces electrical signals from the X-rays so that they can be readily processed and sent to Earth. A rather sophisticated set of electronics not shown in figure 65 is used in this experiment.

Like other equipment used in our exploration of the Moon and space, this equipment is the most ad-

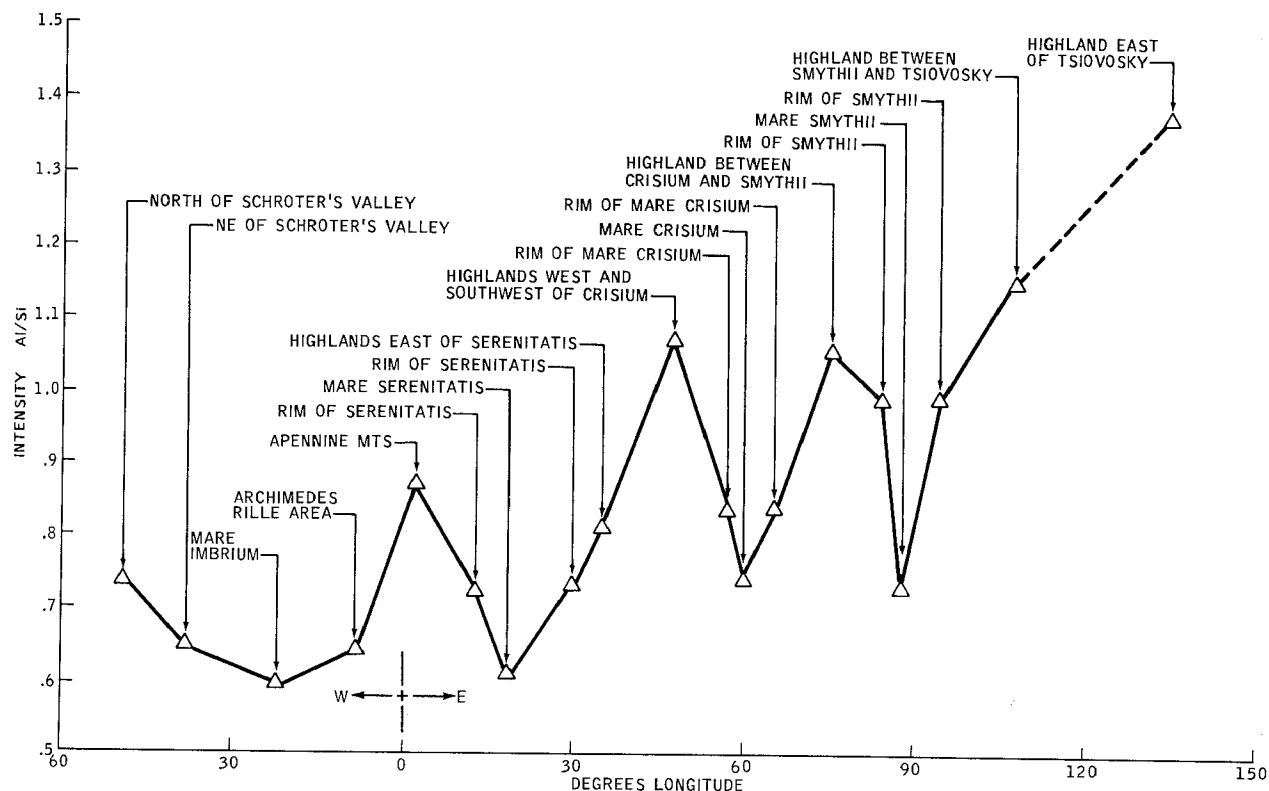


FIGURE 66.—Aluminum-silicon ratios measured along one track of Apollo 15. Note the excellent correlation between the intensity and different lunar regions. The maria have low ratios, the Highlands have high values. These data support the idea that the lunar Highlands consist mostly of anorthosite, an aluminum silicate rock. Similar data will be obtained with identical equipment on Apollo 16. Data provided by Dr. I. Adler, the Principal Investigator of this experiment. NASA PHOTO S-72-16319.

vanced possible. It represents our very best effort at designing and building equipment with extremely high reliability, small size, and low weight. In many instances, we have actually advanced considerably the knowledge needed to design and build equipment.

Some preliminary results have been obtained from the Apollo 15 flight which also carried the XFE. See figure 66. The ratio of aluminum to silicon (usually denoted Al/Si) is plotted against longitude for one revolution. Shown also are the locations of various features of the Moon in relation to the data. The principal investigator, Dr. Isadore Adler, and his team have observed that the ratios are generally low over Mare regions and high over the Highlands. Such systematic variations are clearly related to the distribution of rock types over the surface of the Moon. But the whole story is a complete chapter in itself and, although extremely interesting, is much too long to pursue here.

In addition to its use in studying the Moon, the XFE equipment has another, very important use

in X-ray astronomy. Yes, we *can* "see" things in space with X-rays. About a hundred X-ray sources have been discovered outside our solar system. Some of them also produce radio waves. Some are very faint stars. But their main radiation of energy is in the form of X-rays. Frankly, we do not yet understand the nature of these very distant objects. The great advantage of looking with X-rays from spacecraft rather than from Earth is due to the absorption in the Earth's atmosphere of practically all X-rays from space.

Alpha Particle Spectrometer (APS).—Within a few months after the discovery by Roentgen of X-rays, Henri Becquerel discovered radioactivity. He had left a salt of potassium and uranium (which you and I now know are radioactive) on a photographic plate that was enclosed in black paper. He wished to expose the material to sunlight in order to see if sunlight produced any effect on the salt that could be detected photographically. After several cloudy days though, he decided to develop the film anyhow. Imagine his surprise when the outline of the crystals showed

clearly on his plate indicating that the crystals emitted rays which affected the photosensitive emulsion.

He soon discovered that there were in fact two kinds of rays. One he called alpha rays, the other beta rays. A few years later, a third, termed gamma rays, was also discovered. Today, we know that radioactive substances, like uranium and radium with which I am sure that you are familiar, change slowly but spontaneously into other substances and in the process of changing produce alpha, beta, and gamma rays.

The beta particles, or beta rays (the two phrases are used interchangeably because characteristics of both rays and particles are shown) are really just electrons. Becquerel soon learned that the alpha particles (alpha rays, if you wish, because both characteristics are shown) were very energetic. They could travel several yards in air and could penetrate thin sheets of metal. In addition, they were deflected by magnetic fields. We now know that the alpha particles are just helium ions. It is the distribution of alpha particles over the surface of the Moon that we hope to measure with the APS. Let's see why that information might be of value to us.

The study of samples of both rock and soil returned to the Earth from the Moon shows that uranium and thorium are present in significant amounts. Do not let me mislead you. The key word here is significant. The amount is extremely small. For example, in some of the lunar rocks neither of these two elements is present in quantities larger than a few parts in ten million. Thus, in ten million pounds of such rock we would have only a few pounds of uranium scattered throughout it. For mining purposes, this amount is far too small. Yet for scientific purposes, it is highly significant and can be easily measured with modern instruments.

Both thorium and uranium are radioactive. Hence, both change spontaneously into other materials. The final product of the decay process of each of these two elements is lead. One of the intermediate products of each element is radon, a gas.

Early in the investigation of radioactivity, it was discovered that some elements seemed to have different mass but otherwise identical properties. For example, it was found that while uranium and thorium both ultimately decayed to lead, the mass of the lead that was produced by uranium was different from the mass of the lead produced by thorium. Yet the two kinds of lead were identical

in practically all other properties. In modern day language, we refer to these two kinds of leads as isotopes. I am sure that you are already familiar with the terminology, if not quite familiar with the concept. For example, you have probably heard of, or seen, uranium-238. In scientific notation, this is written ^{238}U . It signifies uranium with a mass of 238. Other uranium isotopes are ^{237}U and ^{235}U .

One of the intermediate products of the radioactive decay of uranium is the gas, radon ^{222}Rn . Thorium also produces radon, but it is the isotope ^{220}Rn . All radon is also radioactive and changes spontaneously to still another material. The rate of change of the two isotopes is greatly different. Half of the initial amount of ^{222}Rn (from uranium) will still be present after 3.8 days (termed half-life). But it takes only 55 seconds for half the initial amount of ^{220}Rn (from thorium) to change.

In designing the APS experiment, we used the following facts: the amount of Th and U present in a rock depends approximately on the rock type; the decay of both Th and U produces radon; radon, being a gas, diffuses through soil and cracks in rocks to the surface of the Moon where it then follows a ballistic trajectory (a short and efficient way of saying that it follows the same path as a bullet would if shot from a gun) above the surface of the Moon to some other point on the Moon. You might be interested in knowing that the initial velocity of these gas particles is about 500 ft/sec and that typically they reach an altitude of 5 miles before they fall back to the Moon's surface. Practically none escapes from the Moon. So, how in our APS experiment, orbiting at 60 miles, can we measure the radon present at 5 miles, or less, in order to infer the rock type immediately below?

Let's see.

When radon decays spontaneously to the next material in the series, it produces alpha particles. These alpha particles can travel much higher above the Moon and hence will be picked up by our instrument. Thus the radon is detected by measuring the energies of alpha particles.

The equipment for the APS and the X-ray experiment, both part of the same assembly, is shown schematically in figure 67. The location is shown in figure 58. The alpha particle detectors are solid state devices that produce an electrical signal when hit by an alpha particle. The electrical signal is amplified, processed, and the data sent back to Earth. The field of view of the instrument

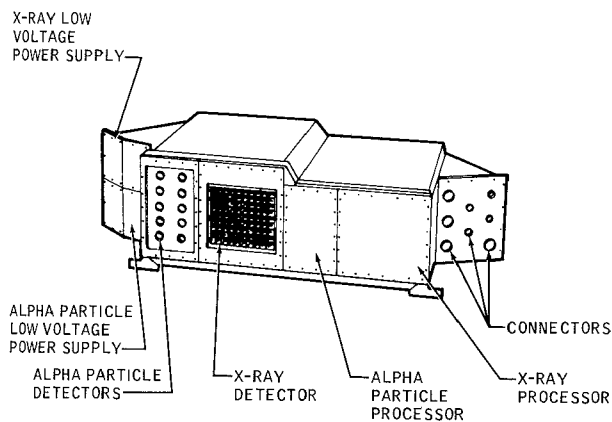


FIGURE 67.—X-ray Alpha Particle Assembly. See discussion in text. NASA PHOTO S-72-16334.

is about 45° which means that the detector “sees” an area of about 120 square miles. Therefore the data that we hope to obtain with the APS on Apollo 16 will represent averages for rather large areas.

Gamma-ray Spectrometer (GRS).—In the decay of radioactive materials, alpha, beta, and gamma rays are produced. Of the three, the gamma rays are the most penetrating. Therefore gamma rays that are produced on the Moon’s surface, or within a few millimeters of it, may be detected and measured with equipment on board the SM. Be-

cause gamma rays with certain energy and wave lengths are characteristic of certain kinds of rocks, we may infer the composition of the Moon’s surface from our measurements. The chief purpose of this experiment is to map the distribution of kinds of rocks over the surface of the Moon. Such information may yield valuable evidence on the origin and evolution of the Moon.

Location of the equipment in the SIM is shown in figure 58. The heart of the equipment, the detector, is shown schematically in figure 68. During operation, it is extended about 25 feet from the spacecraft on a boom. The detector contains a crystal which responds to an incident gamma ray by emitting a pulse of light. The light pulse is converted by a photo-multiplier tube into an electrical signal with strength proportional to the energy of the gamma ray. The electrical signal is then processed and sent to Earth over the radio telemetry channel. The photo-multiplier tube is an advanced form of light sensitive vacuum tube with which you may be familiar; the simpler ones are used sometimes in elevators to hold doors open for passengers, in electrically operated doors, in burglar alarm systems and so on. They are especially popular with hobbyists.

The detector crystal will produce a light pulse from the passage of any charged particle also. Yet we wish to “see” only the gamma rays. To eliminate these effects, the crystal is surrounded by a

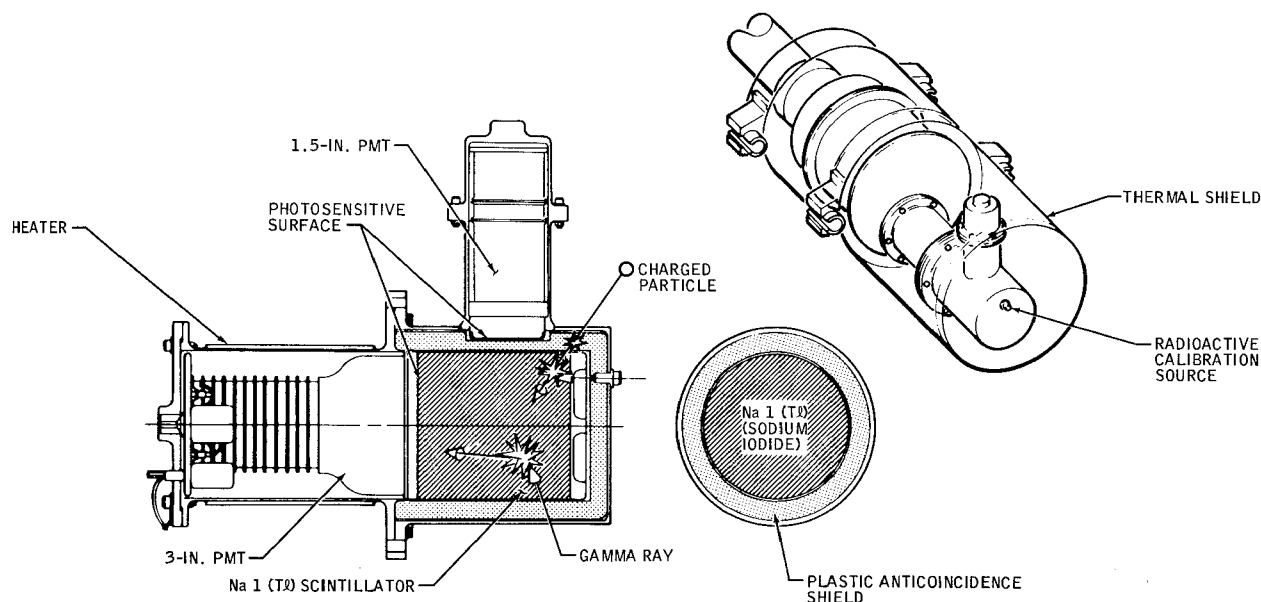


FIGURE 68.—Gamma Ray Detector. The detector, in use, is located 25 feet from the spacecraft on a boom. See discussion in text. See figure 58 for location in the SIM of the gamma ray equipment.

second material which emits light from charged particles but not from gamma rays. Thus the two can be distinguished. The electrical signals produced by charged particles are cancelled in the electronics processing and no false data are generated.

A gamma ray spectrometer similar in all respects to the Apollo 16 equipment was flown on Apollo 15. The final results of that experiment are not yet available but the hardware worked correctly and the analysis is now in progress. I expect that the results will be significant and that they can be correlated with the geological features of the Moon. One feature of the data appears to be a high concentration of radioactivity in Oceanus Procellarum (relative to the rest of the Moon).

Mass Spectrometer Experiment (MSE)

In this experiment we measure the composition and density of gas molecules along the flight path. Early instruments and the basic technique were developed shortly after the turn of the century. The principle can be understood by referring to figure 69. Gases enter the instrument through an inlet manifold, termed plenum, and pass through an electron beam. The electrons in the electron beam knock loose one or more electrons from the gas molecules to produce ions. An ion is merely a gas molecule which has lost one or more electrons. It has both mass and charge. The ion proceeds on through the instrument and is focused into a narrow beam. It then passes through a *magnetic* field. Now the flow of charged particles constitutes electric current flow. And we all know that current

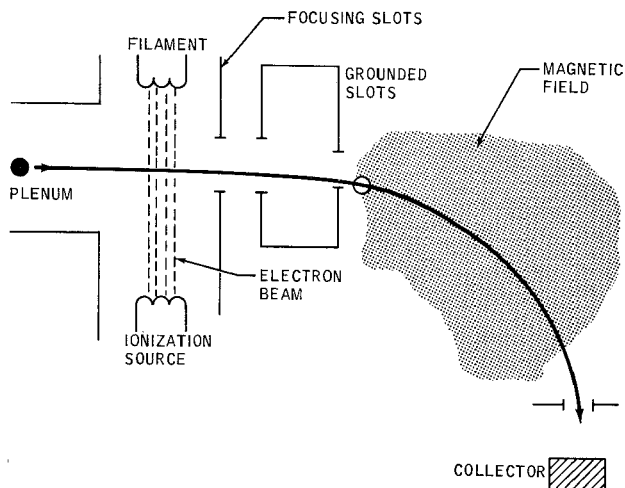


FIGURE 69.—Principle of the Mass Spectrometer. The magnetic field is perpendicular to the plane of the paper. See discussion in text.

flowing in a magnetic field will have a force exerted on it. This statement is the basic principle of all electrical motors. It is one of the basic concepts of physics. It was discovered many years ago. Each time that you start your automobile engine, you close a switch which causes current to flow in a conductor through a magnetic field with the result that a force is exerted on the conductor and (hopefully, at least for my car) the engine starts.

In the spectrometer, the force that is exerted on each ion depends upon the strength of the magnetic field, upon the velocity with which the ion is moving, and upon the number of electrons that were lost. In the magnetic field, the ion follows a circular path. The radius depends, in addition to the factors just mentioned, upon the mass of the ion. By changing the velocity with which the ions travel and measuring the number of ions that pass through the small opening into the collector, we can, in effect, determine the masses of the ions that are present. Essentially this same procedure is used in the Apollo 16 mass spectrometer.

In the Moon's atmosphere, which as you know is extremely thin, we expect to find such light gases as hydrogen, helium, and neon, with neon probably 10 times as abundant as the others. These gases come from the solar wind. Argon is likely present from the decay of radioactive potassium (^{40}K). Certain other gases, such as carbon dioxide, carbon monoxide, hydrogen sulfide, ammonia, sulfur dioxide, and water vapor may have been produced by lunar volcanoes.

In operation, the spectrometer is about 25 feet from the spacecraft at the end of an extended boom. The location of the instrument in the SIM is shown in figure 58.

On Apollo 15, about 40 hours of data were obtained in lunar orbit and about 50 hours were obtained during the transearth coast. Many gases were clearly present. The data have not all been analysed at the time of writing this booklet and I cannot give you the final interpretation. But at first look, it seems that rather significant quantities of gas are in orbit around the Moon; there was also a decrease by a factor of 5 to 10 in the amount of gas measured during the trip back to Earth. Perhaps the liquids dumped from spacecraft in orbit around the Moon remain much longer than we had expected. Perhaps. But that explanation is just speculation at this time. We really don't yet understand why the Apollo 15 instrument saw so much gas in its orbits around the Moon.

S-Band Transponder (SBT)

With the S-band transponder we measure very small *variations* in the Moon's gravity. I am sure that you know the Moon's gravity is only about one-sixth that of the Earth's. But did you know that the exact value changes significantly over the face of the Moon?

In order to see how the SBT works, think about the following situation. Suppose that the Moon is like a ball, perfectly round and homogeneous throughout. For a circular orbit around such an ideal Moon, there would be no variations in the velocity of the spacecraft. But suppose that we have at one spot buried just beneath the surface a very large chunk of material with very high density. Just for thinking purposes, let's suppose that this large chunk is 50 miles across and is twice as dense as the rest of the Moon. Consider figure 70. As the spacecraft approaches the dense chunk, at position 1, there is a gentle tug in the forward direction due to the gravitational attraction between the spacecraft and the dense chunk. That slight tug is enough to cause the CSM to speed up slightly. At position 2 all of the force is directed downward and there is no net increase, nor decrease in the horizontal velocity of the CSM. Finally in position 3, the spacecraft experiences a backwards pull on it and accordingly, the velocity decreases slightly. Now this change, even though

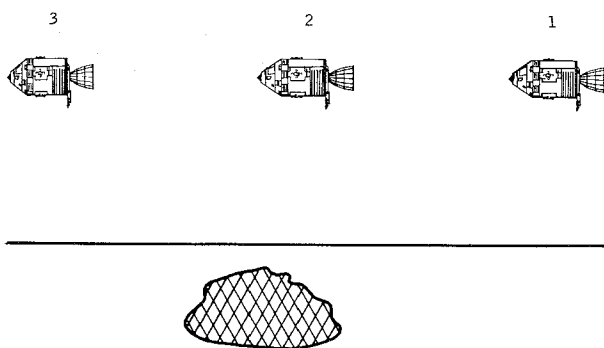


FIGURE 70.—Effect of density on Spacecraft Velocity. Suppose that a large chunk of material of high density is buried beneath the surface of the Moon. The spacecraft at position 1 will be pulled gently forward by it. At position 2, there will be only a net downward force and no horizontal force. At position 3, the high density material will pull gently backward on the spacecraft. Because of these forces the spacecraft speeds up slightly at 1 and slows slightly at 3. Of course these changes to the velocity of the spacecraft are really very small but can be easily measured with electrical means. See further discussion in text.

it is very small, in the velocity of the orbiting CSM can be measured with extremely high precision.

These high precision measurements of the changes in velocity are obtained in the following way. From Earth a radio wave of very stable frequency* of 2115 MHz is transmitted to the orbiting spacecraft. When the radio wave is received by the spacecraft, the frequency is multiplied by the constant 240/221 (for electronic reasons) and then retransmitted to Earth. The frequency of the signal when it arrives back on Earth, though, is usually slightly different from the original frequency multiplied by 240/221. Let's see why. The radio waves sent by a moving source (the CSM) behave in exactly the same way as sound waves sent by a moving source. I am sure that most of us recall that a whistle on a train changes pitch considerably when the train passes us. The whistle is higher in pitch when the train is approaching than when it has already passed. The same phenomenon, termed Doppler shift, occurs when radio waves are transmitted from a moving source. In fact, the shifts that are observed are sometimes as large as several hertz. We measure these shifts with a resolution of 0.01 hertz. Thus we are able to measure very small changes in velocity of the spacecraft.

The basic data of the SBT experiment are the variation in velocity of the spacecraft along its path. From them, we deduce the changes in the Moon's gravitational field. This technique has been used on many of the spacecraft that have orbited the Moon. The earliest was done on the Lunar Orbiter series with the beautiful result shown in figure 71. Shown in that figure are the *variations* in gravity. The main part of the gravity field has been subtracted from these data and we are looking only at the *departures* from normal gravity. I personally think the discovery by Paul Mueller and William Sjogren of the Jet Propulsion Laboratory of these variations of gravity over the face of the Moon ranks as one of the most important scientific discoveries about the Moon.

On Apollo 16, the S-band transponder experi-

*The unit megahertz is one million cycles per second. I am sure that you are already familiar with the concept of frequency; exactly the same concept is used for AM radio (frequency of .54 to 1.6 MHz), FM radio (frequency 88 to 108 MHz), VHF television (frequency 54 to 216 MHz), UHF television, and so on. The frequency that we use for the S-band transponder experiment is somewhat higher than any of those, but the concept is exactly the same.

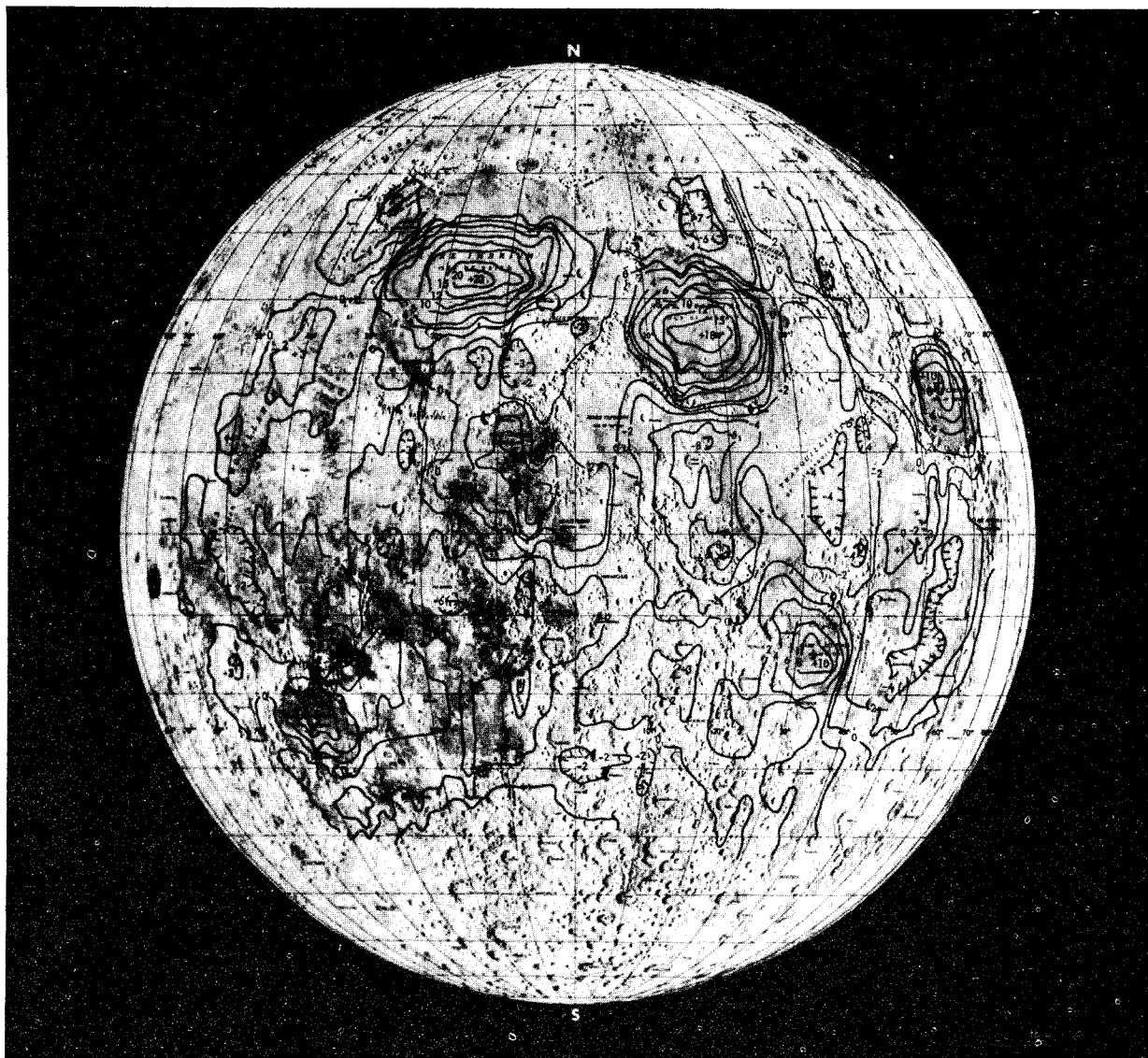


FIGURE 71.—Lunar Gravity. These lines, called contour lines, show the departures from “normal” gravity on the front side of the Moon. The units are 100 milligals. The difference between adjacent lines, termed contour interval, is 200 milligals. To obtain total gravity, you must add the usual $\frac{1}{6}$ of the Earth’s gravitational field to these values. Mueller and Sjogren, working at the Jet propulsion Laboratory, first found these very large variations in the Moon’s gravitational field by measuring the very small changes in the velocity of orbiting spacecraft. Notice the excellent correlation between the gravitational feature and the surface features of the Moon. The discovery of these variations in the gravitational field surely ranks as one of the most important in Lunar Science. NASA PHOTO S-72-16340.

ment will obtain data from three spacecraft, the orbiting CSM, the LM, and the subsatellite. Because the subsatellite will stay in lunar orbit for many months, and possibly several years, many new data should become available from it.

One big advantage of this experiment is that it allows us to “see” below the surface of the Moon. The differences in density of the rocks beneath the surface of the Moon produce the differences in

the gravitational field which, in turn, affects the velocity of the spacecraft. Thus we have a tool with which to examine the distribution of the rocks beneath the surface of the Moon. It is a tool that we have found to be very effective in our exploration of the Earth’s crust. We are especially anxious to see whether there are large variations in density beneath such topographic features of the Moon as the large craters.

Bistatic Radar Investigation

Even in space exploration, one sometimes gets something for (almost) nothing. Such is the case with the bistatic radar investigation. In this experiment, we study the radio signal that is normally used in communications between the CSM and Earth. We compare the signal that comes directly to Earth from the orbiting CSM with the signal that is reflected from the Moon's surface. These relations are shown in figure 72. The type of antenna used to receive these rather faint radio signals is shown in figure 73. From a comparison of these two signals, we are able to learn several things about that part of the Moon immediately below the orbiting CSM. We are able to measure certain electrical properties of the outer few yards of the Moon's crust, determine the average slope of the Moon's surface, and detect rocks buried to depths of perhaps 50 to 60 feet. Such data will

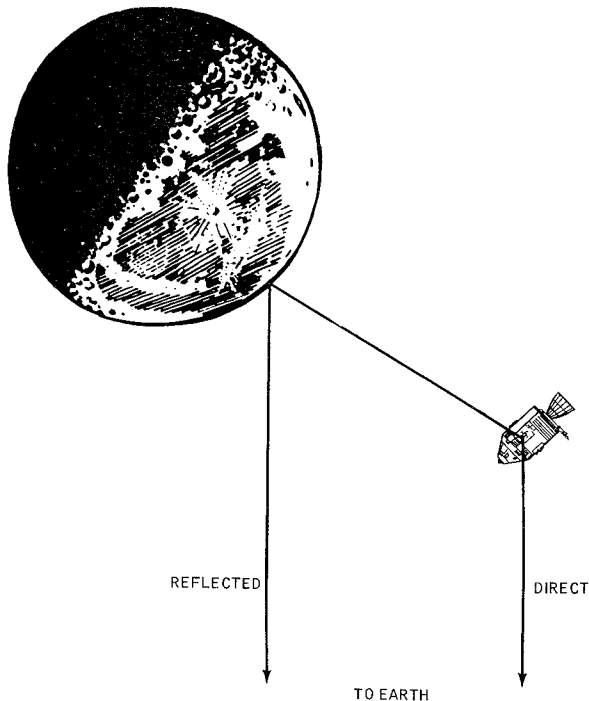


FIGURE 72.—Bistatic Radar Experiment. The radio communication signals from the spacecraft travel along two paths. One comes directly to the receiving antennas on Earth. The other travels to the Moon, is reflected, and then travels directly to the receiving antennas. Comparison of these two signals allows us to recognize the changes caused by the reflection from the Moon. Such changes are the basic data of this experiment from which we infer the electrical properties of the outer few yards of the Moon. The Moon and spacecraft are not shown to the same scale.

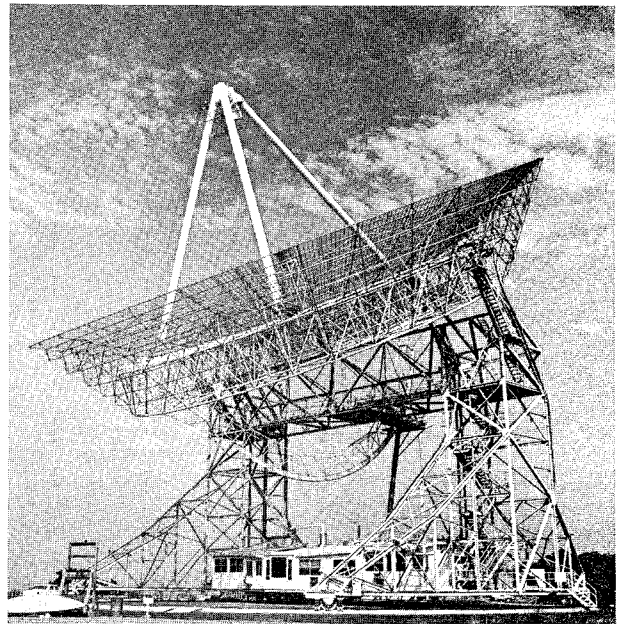


FIGURE 73.—The large radio receiving antenna at Stanford University. This unit collects the energy received as radio waves over the 150 foot "dish" and focuses it at the small feature, termed feed point, seen near the center. It is then sent through high quality amplifiers. This antenna and similar ones located at several sites around the Earth (so that the Moon is always in view) are used both to communicate with spacecraft and to measure their changes in velocity. See text for further discussion. PHOTO COURTESY OF H. T. HOWARD.

be extremely useful when synthesized with the other information from the Moon.

Subsatellite Experiments

Carried in the Apollo 16 SIM is a small, 85 lb., scientific spacecraft that will be placed in orbit around the Moon and left there when the astronauts return to Earth. It is the particles and fields subsatellite or subsatellite for a shorter name. Its location is shown in figure 58. It is sketched in figure 74. This satellite is completely self-contained. It carries its own power supply (solar cells that deliver 24 watts), solar sensors (to let us know the direction in which the satellite is pointing), a battery pack of silver-cadmium cells (for power when the satellite is in the shadow of the Moon), a data storage unit (magnetic core memory, similar to those used in some large computers), an S-band communications system, and the equipment for two scientific experiments. Data that are obtained on the backside of the Moon are stored in the memory unit and then, on command from the Earth when the satellite is in view, sent to

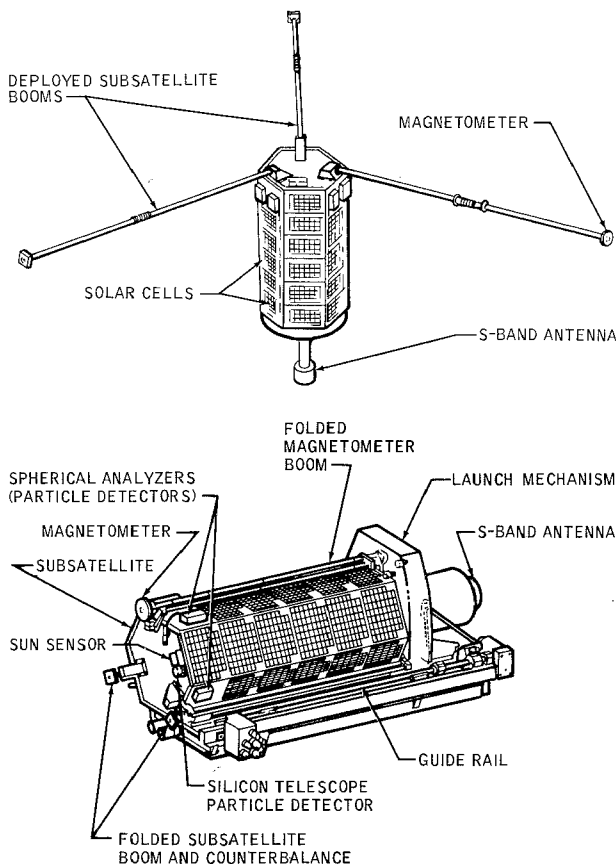


FIGURE 74.—The Apollo 16 Particles and Fields Subsatellite. In the lower figure, the subsatellite is shown in the folded configuration in which it is carried in the SIM. It rests on a guide rail. On command from the CM, it is ejected from the SIM and assumes the configuration shown in the top figure. It remains in orbit at least several months and possibly years. NASA PHOTOS S-72-16304 and S-72-16311.

Earth in about 8 minutes. A similar satellite was left behind in lunar orbit by the Apollo 15 crew. It is still sending data to us. I will use some of the results obtained with it for illustration.

The subsatellite carries two experiments, one to measure particles and the other to measure magnetic fields. A third experiment, the S-band transponder, requires no additional equipment on the satellite and is entirely passive; it is discussed in the section "S-band transponder" elsewhere in this guidebook.

In order to understand clearly the purpose of the magnetometer and particles experiments, let me discuss briefly some space physics. The Earth has a magnetic field. It is convenient for most of us to visualize that magnetic field as having "field

lines." You may remember that iron filings placed on a sheet of paper over a magnet will stand on end and, in fact, line up with the individual magnetic field lines. We can visualize the magnetic lines of the Earth as being similar to those shown in figure 75. However, the field lines for the Earth are really not quite like I have shown them in figure 75. In fact, on the side of the Earth towards the Sun, the field lines are compressed; on the side away from the Sun the field lines are stretched. They extend in very long loops. This correct situation is shown in figure 76. We have verified this concept of the compression and stretching of the Earth's magnetic field lines shown in figure 76 with measurements made from previous satellites equipped with magnetometers.

The Sun has streaming out from it continuously a very thin gas that is composed of electrons, protons, hydrogen, helium, neon, certain other gases and other nuclear particles. (These are the elements we can measure directly; presumably all other elements are present too.) This very thin gas from the Sun is called the solar wind. The solar wind "blows" the Earth's magnetic field lines around behind the Earth. Different regions with different characteristics are known by different names. The large region behind the Earth with relatively few lines is called the geomagnetic cavity; it extends out to a distance at least 100 times the Earth's radius. We do not know how much further it may extend. We have not had satellites in the more distant region for measurements. The region around the cavity is disturbed by the interaction of the solar wind and the Earth's magnetic field. It is the magnetosheath.

The Moon rotates about the Earth at a distance

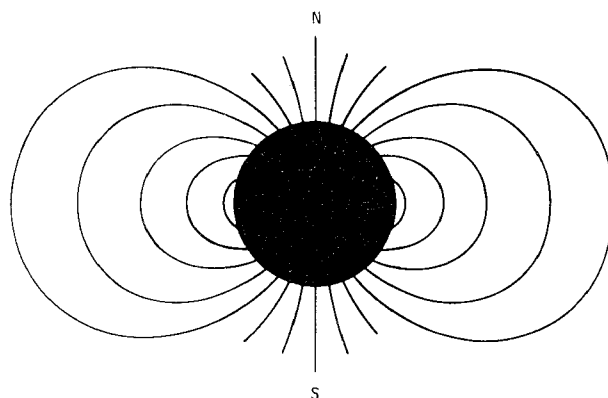


FIGURE 75.—Idealized Magnetic Field of the Earth. In the absence of the solar wind, the magnetic field lines of the Earth would be symmetrical about the Earth.

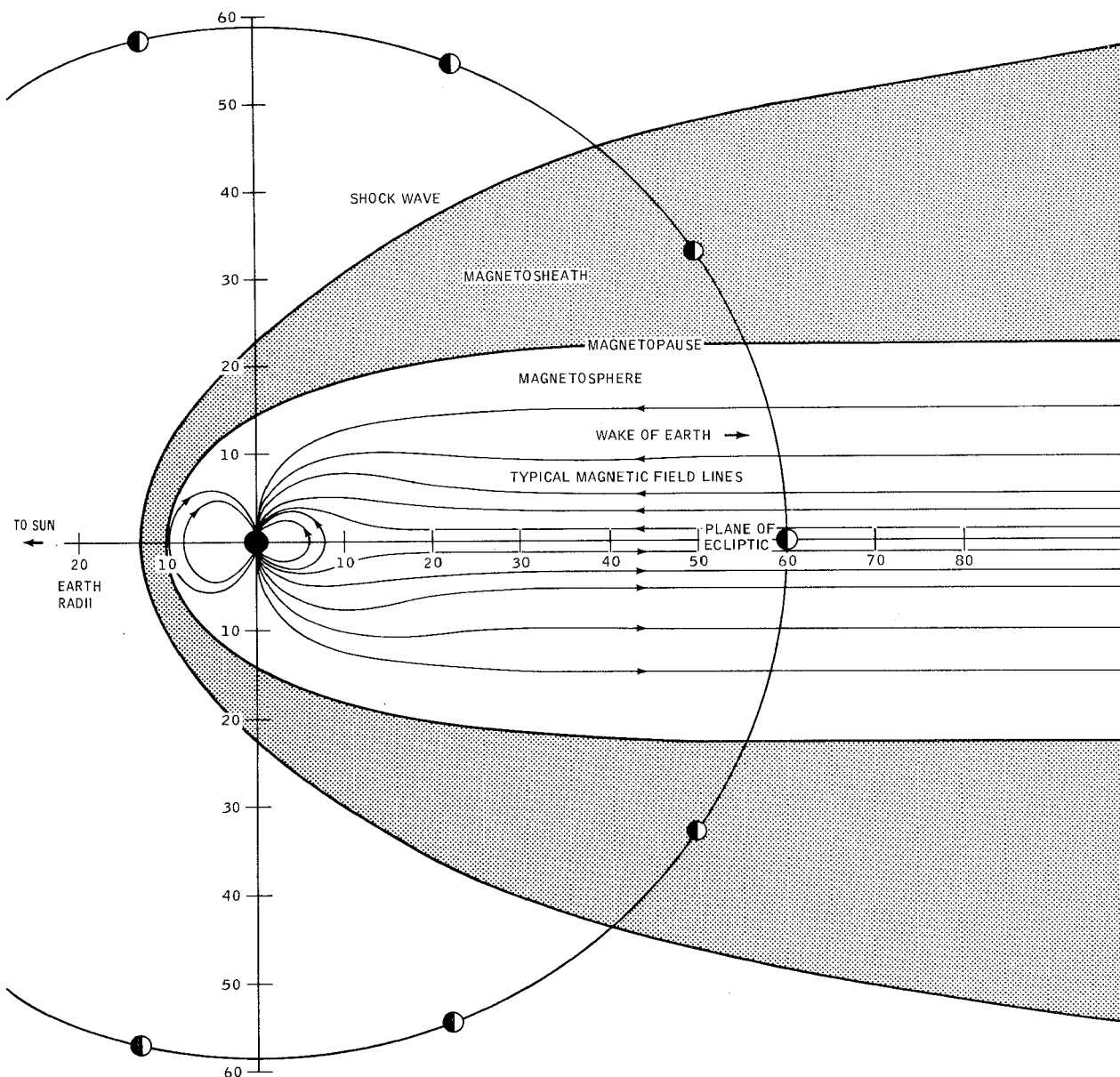


FIGURE 76.—Observed magnetic field of the Earth. The solar wind “blows” the magnetic lines toward the back side of the Earth forming the magnetosheath and the geomagnetic cavity. The geomagnetic cavity extends to at least 100 earth radii. The Earth and Moon are not sketched to scale. The Moon completes an orbit about the Earth every 28 days. NASA PHOTO 8-72-16821.

of 60 Earth radii, 240,000 miles. Thus the Moon passes through a part of interplanetary space in which there is almost no effect from the Earth's magnetic field; it also passes through the magnetosheath and the geomagnetic cavity. These different regions affect the solar wind and magnetic fields on the Moon in different ways. Thus in order to interpret a particular set of data from either the magnetometer or from the particle experiment, it

is necessary to know the location of the Moon with respect to the Earth and Sun when the data were taken.

The Moon has a very small magnetic field, less than one-thousandth that of the Earth. It interacts with the solar wind in a completely different way than does the Earth. The Moon acts as a barrier. In the absence of a significant magnetic field, the solar wind on the front side of the Moon simply

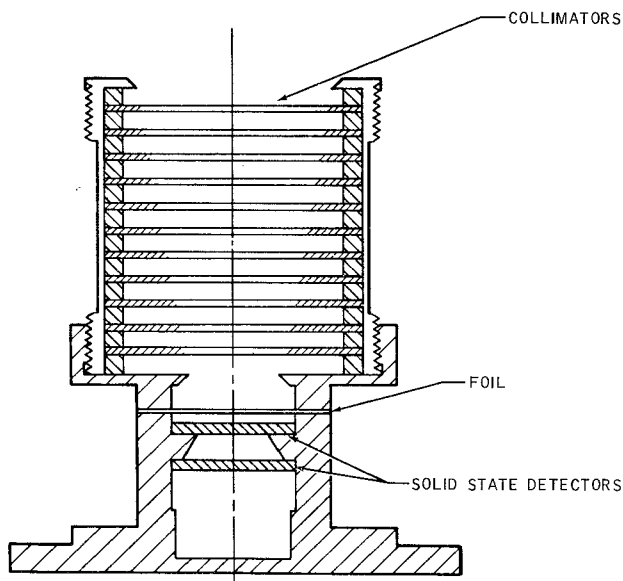


FIGURE 77.—Particle Telescope. The collimators are used to restrict the field of view. The foil is used to distinguish between protons and electrons. The solid state detectors are sensitive to both protons and electrons. Two of these units (one without the foil) are used in the Apollo 16 subsatellite. Based on a similar sketch by Anderson and others in Apollo 15 Preliminary Science Report.

strikes the Moon. Thus there is a “shadow” cast by the Moon.

The chief objectives of the particles experiment are to (1) describe the various features of the plasma through which the Moon moves, (2) to measure the interaction of the Moon with the plasmas, and (3) to investigate the structure of the Earth’s magnetosphere. In order to accomplish these objectives, we must have an instrument that will detect and measure the charged particles. In figure 77, I show schematically one of the two particle telescopes. Basically, it is a tube with collimators to restrict the viewing angle and solid state detectors. With these instruments and the associated electronics, we can measure the direction and the energy of the charged particles—either electrons or protons. We can also distinguish between electrons and protons. An example of the data obtained on Apollo 15 is shown in figure 78. There I have plotted the relative number of electrons as a function of the position of the spacecraft.

Let’s discuss the other experiment on board the subsatellite, the magnetometer. We already have magnetometers on the Moon. At the Apollo 12 and 15 sites, there are surface magnetometers of the

kind described elsewhere in this booklet which are still operating. At the Apollo 14 site, we used a portable magnetometer to obtain two measurements of the steady field.

In addition, an orbiting magnetometer on the Explorer 35 satellite has operated for several years and continues to operate. So how could we possibly need another magnetometer on the subsatellite? For several reasons. First, the three station magnetometers operating on the Moon’s surface (Apollo 12, Apollo 15, and after this mission Apollo 16) measure the variation of the magnetic field with time. In order to best interpret those data, we need independent measurements of the changes with time of the magnetic field in space. The orbiting magnetometers (Explorer 35, Apollo 15 subsatellite, and now Apollo 16 subsatellite) will give us the information necessary to make the best interpretation of the data that we collect on the surface of the Moon. Secondly, since the Explorer 35 is orbiting at several hundred miles from the Moon we cannot obtain information about variations in the magnetic field near the surface of the Moon.

One of the big surprises in the Apollo science program was the discovery that the magnetic field at the surface of the Moon was much larger than we had predicted on the basis of measurements taken with the orbiting satellite, Explorer 35. A permanent magnetic field of 38 gamma was measured at the Apollo 12 site. Two measurements made by the Apollo 14 astronauts, separated by about 3,500 feet in the Fra Mauro region were 103 gamma and 43 gamma. From those measurements

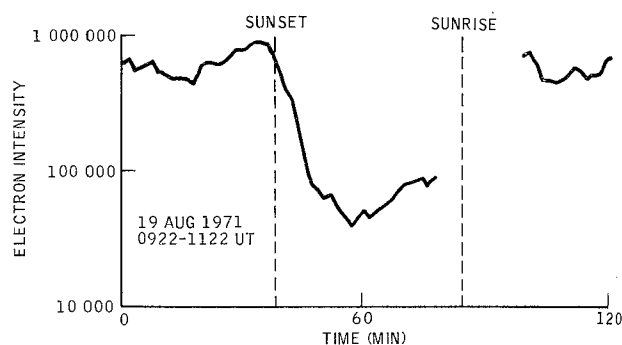


FIGURE 78.—Relative Numbers of Electrons measured with the Apollo 15 Particle Telescope on August 19, 1971. The large decrease is caused by the Moon’s shadow. The break in the curve is due to lack of data. Based on work by Anderson and others reported in the Apollo 15 Preliminary Science Report.

it was clear that the Moon's permanent magnetic field is significantly different at different locations. With a magnetometer flown in an orbit close to the Moon's surface, like the Apollo 15 and 16 subsatellites, we hope to measure the variations over the Moon of the permanent magnetic field.

In addition to the static magnetic fields of the Earth and Moon, there exist electromagnetic fields that propagate through space. The measurement of their interaction with the Moon allows us to infer the electrical conductivity of the interior of the Moon. In fact, as discussed elsewhere in this booklet, the chief purpose of the Lunar Surface Magnetometer (LSM) is to make such measurements and to use them to determine the electrical properties of the interior of the Moon. Now the Moon acts as a shield for these propagating fields.

If we are interested in measuring the permanent magnetic field of the Moon, then we can best obtain those data by making measurements on the side of the Moon that is away from the Sun. The variations with time of the magnetic fields from space are very small there. See figure 78. A preliminary examination of some data obtained with the Apollo 15 subsatellite from the far side of the Moon suggests that the very large craters, those over 60 miles across, have permanent magnetic fields associated with them. If this preliminary result proves to be valid, then we shall have a truly remarkable result and will undoubtedly use magnetic methods to study craters. Because we will obtain several readings with a portable magnetometer on the surface at the Apollo 16 site, it is possible that we may be able to provide additional evidence.